High Resolution Mapping of ^{137}Cs and ^{7}Be Inventories in the High Deposition Area of Southern Lake Michigan

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Introduction

A recently completed (LMMB) study of fine-grained sediment deposition in Lake Michigan reveals that modern deposits accumulate preferentially along a 40 km wide band, extending 350 km from south to north, located approximately 20 km offshore from the eastern side of the lake. (Fig. 1). Early geological work in the southern Lake Michigan, suggested that markedly asymmetric allocation of sediments to the lake floor reflected the predominance of loads from several major tributaries on the eastern side. However later investigations have demonstrated that rivers contribute comparatively little (ca. 16%) to the total inventory of fine sediments. Nearly 70% is contributed by erosion of bluffs located primarily on the western side and an additional fraction (16%) comes from deposition of atmospheric particles. Thus particle entry points to the lake are generally quite remote from primary regions where sediments finally accumulate.

Our understanding of the processes responsible for the conveyance of particles from sources to sedimentary sinks, has vastly improved during the past several decades through satellite imaging, sediment trap studies, plus hydrodynamic measurement and modeling. Particles eroded from western shoreline bluffs entering the lake, may quickly settle to the bottom only to be re-suspended, moved laterally along- and off-shore by currents and re-deposited. Over many years, cycles of re-suspension and re-deposition ultimately deliver particles to final deposition sites. It is presently thought that annually recurring, episodic late winter storms with high winds, set up strong circulation patterns in the un-stratified lake that are largely responsible for such incremental redistribution of sediments. In southern Lake Michigan such storms often generate turbid surface waters over the HiDep area (Fig. 1, rectangular inset area).

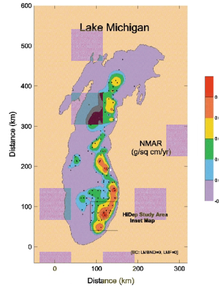

Fig. 1. Net mass accumulation rate (NMAR) contour map for Lake Michigan based on ^{137}Cs and ^{210}Pb profiles in 134 box cores collected between 1992 and 1996 as part of the EPA supported Lake Michigan Mass Balance (LMMB) Study. The rectangular inset locates the High Deposition Study (HiDep) Area.

This Study

The aim of this study was to assess the contribution of such late-winter episodic re-suspension events (EREs) to the magnitude and pattern of net sedimentation in the HiDep area. To this end, we used particle-tracking radionuclides, ^{137}Cs ($t_{1/2}$=30 years) and ^{7}Be ($t_{1/2}$=53 days), respectively, to infer long- and short-term patterns of particle accumulation. The HiDep area brackets sites with highest mass accumulation in Lake Michigan and has been intensively studied as part of the EEGLE Program. It also encloses the region with the greatest thickness (>9 m) of sediments in the Waukegan Member (ca 3500 b.p.) of the Lake Michigan Formation (Fig. 2, contours). This member is thought to reflect present distributions of shoreline, watershed and internal sources of particles delivered to sediments. Comparison of Figures 1 and 2 confirms that allocation of modern sediments in the southern lake is indeed consistent with the historic deposition pattern.

On five separate cruises, from September 1998 through June 1999, modified Soutar type box cores were collected from the selected sites within the HiDep area (Fig 2, solid circles). Cruises were timed to occur before, possibly during, and after anticipated EREs: September 1998, Nov 1998, Jan-Feb 1999, March-April 1999 and June 1999. On each cruise a slightly different array of stations was visited so as to produce a composite array of unusually high spatial resolution. On the November cruise, too few sites were cored to produce a meaningful array for contouring. Cores were sectioned aboard ship in two segments: 0-2 cm and 2-50 cm. Segmentation was based on prior observation that detectable activity of 7Be was consistently confined to the upper 1-2 cm of cores. Activity of ^{137}Cs occurred only above 20 cm. Segments were homogenized, freeze-dried, and portions were counted by high-resolution gamma spectroscopy systems calibrated with NIST-traceable standards. The systems are also calibrated for 40K ($t_{1/2}$ = 1.3 x 109 yr) that measures the amount of potassium in sediment samples. In the Great Lakes a dominant source of potassium is the ^{137}Cs-sequestering clay mineral, Illite. Inventories of ^{7}Be were calculated as products of the activity and the cumulative dry mass per unit area of 0-2 cm segments. For ^{137}Cs, the inventory was taken as the sum of inventories in both core segments.

We also made use of mass fluxes and ^{137}Cs concentrations in sediments collected by an automated sequencing trap positioned 30 m above bottom at a centrally located 56 m deep site in the HiDep area. Over the course of a year, starting on 15 August 1995, the trap collected 24 samples in separate containers each of which received settling material for 15 days. Collected sediments were protected against decomposition by addition of 6 ml of $CHCl_3$ plus 55 ml of distilled, de-ionized water to each 60 ml container at the time of trap deployment.

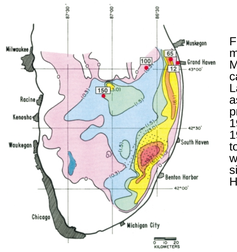

Fig. 2. Thickness the sediment in the Waukegan Member (from present to ca. 3500 years b.p.) of the Lake Michigan Formation as determined by seismic profiling (Lineback et al., 1972). From September 1998 through June 1999, a total of 169 box cores were collected from the sites shown within the HiDep area.

Inventories of ^{137}Cs and Mass Accumulation Rates

Nearly all ^{137}Cs entered Lake Michigan as fallout from atmospheric testing of nuclear weapons during the period from 1952 though the 1960s. The radionuclide was rapidly removed from the water column on settling particles so that, beyond the early 1970s, essentially 100% of the total amount delivered to the lake resided in bottom sediments. Nevertheless, small amounts of ^{137}Cs-labeled particles have continued to be subject to cycles of re-suspension, horizontal redistribution and intensified focusing. Over many years, the result has been a highly asymmetric lake-wide inventory of ^{137}Cs in sediments (Fig. 3, left) that resembles the pattern of sediment accumulation (Fig.1). High resolution mapping over the HiDep area, shows that the ^{137}Cs inventory is even more focused (Fig 3, right) than indicated from the lake-wide study.

Since sediment cores were not sectioned so as to calculate net mass accumulation rates (NMARs) from profiles of ^{137}Cs and excess ^{210}Pb was not measured at all, we determined NMARs in the HiDep area by an alternative method. In southern Lake Michigan, the relation between NMARs and ^{137}Cs inventories (SACs) and NMARs is well described by the semi-empirical, zero-intercept quadratic (ZIQ) equation: NMAR = A*SAC+B*SAC^2. A least-squares fit of this equation to data (r=0.98 for n=48) is shown as the solid line in Fig 4. We used optimized values of coefficients A and B to calculate NMARs from SACs at each site in the HiDep area. The non-linear ZIQ relationship suggests that as NMARs increase, either less ^{137}Cs was locally available to be scavenged from the water column or more ^{137}Cs-depleted particles were contained in cohorts of particles deposited at higher rates. The resulting NMAR contour map (Fig.5.) shows the band of high sediment accumulation paralleling the shoreline in the southern part of the HiDep grid, then tilting about 30 degrees away from shore in the central part. This pattern, revealed only by high-resolution mapping, is consistent with storm-driven water circulation in the vicinity of the HiDEp area. High winds from the northwest establish a counter clockwise gyre in the southern part of the lake that conveys water northward along shore toward the HiDep area. Within the area, circulation often begins to diverge offshore. The tongue of elevated NMARs extending outward into the central region of the southern Lake (Fig 1) is a geographical if not physical extension of the main axis the tilted NMAR pattern in the HiDep area (Fig. 5).

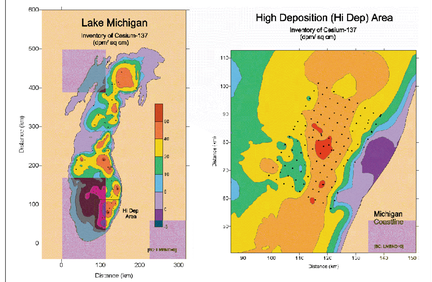

Fig. 3. (left) Inventory (SAC) of ^{137}Cs in Lake Michigan sediments based on LMMB cores. (right) Inventory of ^{137}Cs in the HiDep area sediments based on 169 cores. Note the color scale values are the same for each panel of the figure.

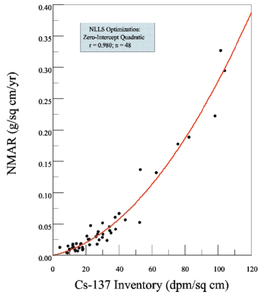

Fig. 4. Quadratic relation between NMAR and SAC based on 48 LMMB cores from the southern part of the lake. Twenty of the LMMB coring sites were located within the inset map of the HiDep area.

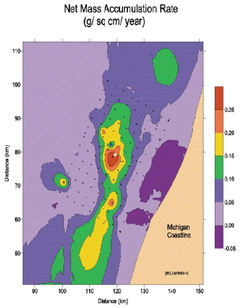

Fig. 5. Net mass accumulation rate contours in the HiDep area. In the southeastern part, the region of highest accumulation parallels the shoreline but then veers offshore to the northwest. The white square locates the sequencing trap site.

Surface activities of ^{137}Cs and ^{40}K

Activities of ^{137}Cs in near-surface (0-2 cm) sediments show an extremely regular, more than 10-fold increase from inshore to offshore sites (Fig 6 left), and tend to conform in detail to the curvature of isobath lines within the HiDep area. The trends cannot be explained by variability in mass accumulation rates since the distribution of rates is highly peaked within the HiDep area unlike near-surface concentrations. Nor can trends be explained in terms of relatively more dilution of inshore deposits by sands (specifically quartz). Box corable deposits in the HiDep area, generally contained very little sand but, more significantly, surface concentrations of ^{40}K (Fig. 6 right) show essentially no inshore-offshore gradient at all over the HiDep area. Most likely, the activity of ^{137}Cs is being systematically diluted by sediments that contain amounts of ^{40}K characteristic of fine sediments (containing Illite) throughout Lake Michigan and in the fine fraction of eroded bluff deposits. It is consistent with the observation that the sustained winnowing of ^{137}Cs-labeled particles from margins of depositional sites and focusing occurs as labeled particles are re-suspended and replaced by non-labeled substitutes with equivalent mineral composition. Hence the observed activity gradient is a non-steady state feature. Over time, the inshore-offshore (decay-compensated) activity gradient should continue to increase.

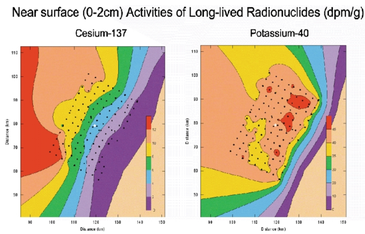

Fig. 6 (a) Activity of ^{137}Cs and (b) ^{40}K in the upper 2 cm of sediment. There is a systematic 10-fold inshore-offshore increase in ^{137}Cs activity while the activity of ^{40}K varies by less than ± 10%.

Trap-Determined Fluxes and ^{137}Cs Activities of Settling Particles

Unfortunately, there are no trap data for the period of this study. However, during four other periods (1994-1995, 1997-1998, 1999-2001 and 2000-2001) there are annual records for the gross downward flux (GDF) of settling matter at the 56 m deep HiDep site. For illustration, we selected the 1994-1995 period partly because the 30 m trap recorded the highest 30 m GDF of the set during the un-stratified period, 0.15 g cm^{-2} yr^{-1}, (Fig. 7, shaded region). The mean 30 m GDF (un-stratified) for the four periods is 0.10 ± 0.03 g cm^{-2} yr^{-1}. The central feature (b) is the massive and sustained flux that occurs from the beginning of January 1994 through mid-March 1995, when bottom sediments were re-suspended and mixed into an un-stratified water column. Three secondary peaks are evident: (a) one in late October 1994, associated with the formation and settling of calcite particles; (c) a second toward the end of April, probably due mainly to the spring diatom bloom and possibly runoff from tributaries; and (d) a third smaller maximum in mid- June, associated with epilimnetic plankton production.

Activities of 137Cs in selected trap samples range from 4.9 to 6.7 dpm g^{-1} and are characteristic surface sediment activities located within about 4 km distance from the trap site, 4.0-6.0 dpm g^{-1} (see Fig. 6 left). Additions of authigenic materials produced in the stratified water column (peaks a, c and d) have only a small diluting effect (ca 15%) on the activity of ^{137}Cs in sediments re-suspended into bottom traps in this region. Also, the potential effects of particle sorting during re-suspension on elemental concentrations sediments collected traps located above fine-grained deposits appears to be minimal (Robbins and Eadie, 1991). Thus, observed activities of ^{137}Cs in settling material above the 56 m HiDep site are consistent with a predominately local source of sediments although strictly local re-suspension and re-deposition of sediment would deliver no net mass to underlying deposits.

No doubt a portion of the 30 m GDF (un-stratified) is locally derived, but even if there were no local contribution and 100% were captured by underlying sediments, the measured mean (0.10 g cm^{-2} yr^{-1}) is far too low to generate the NMAR at this site, 0.25 g cm^{-2} yr^{-1}. Inclusion of 30 m GDFs for stratified periods adds very little to total GDF at 30 m depth. Mean 30 m GDF during the stratified and un-stratified periods are: 0.3 ± 0.3 and 4 ± 7 g m^{-2} d^{-1}, respectively. At 50 m depth (just 6 m off the bottom) GDFs (un-stratified) are significantly higher (up to a factor of 2) than at 30 m. But the increase with depth could be entirely the result of the dynamics of local re-suspension. However, under stratified conditions, GDFs at 50 m have been observed to be extremely high (up to 1000 g m^{-2} d^{-1}) even when 30 m GDFs remained negligible. Also the average GDF 6 m above bottom at this site is essentially the same during the stratified and un-stratified periods: 8 ± 18 and 7 ± 9 g m^{2} d^{-1}. This suggests that horizontal, kilometer scale transport of mass within meters of the sediment-water interface may be important for horizontal redistribution and net accumulation of sediments in the HiDep area

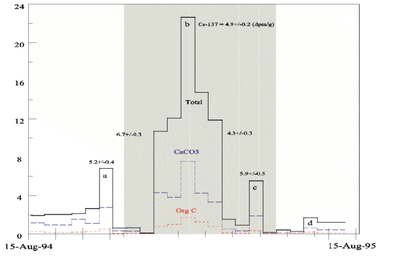

Fig. 7. Seasonal changes in the gross downward flux of total mass (GDF), calcium carbonate and organic matter near the center of the HiDep area. Numbers with standard deviations refer to ^{137}Cs activities of trap samples collected at maximum GDF (a, b and c) and on "shoulders" of the "b" GDF maximum.

Inventories of ^{7}Be

^{7}Be is a cosmogenic radionuclide produced in the atmosphere and delivered to the lake at a seasonally varying rate (Fig. 8a). Deposition rates during the period of core collections varied from a minimum during the winter months of about 60 dpm m^{-2} d^{-1} to a maximum during the summer of about 220 dpm m^{-2} d^{-1}. Delivered to Lake Michigan, ^{7}Be is rapidly and strongly adsorbed to clays, clay sized particles and organic matter. Thus it is a particle tracking radionuclide and, because of its short half-life, ^{7}Be is well-suited to study of particle transport processes on seasonal time scales. The inventory of ^{7}Be in the lake (water column plus sediments), calculated as the time integrated flux corrected for radioactive decay, is shown in Fig 8b. Maximum inventory in the lake was about 1.6 dpm cm^{-2} in September 1998 and a minimum of about 0.8 dpm cm^{-2} in March 1999. Whole lake inventories are used to remove (normalize) seasonal variations in the loading of ^{7}Be when examining changes in inventories over the HiDep area.

The contour map for September 1998 (Fig. 9, upper left) shows a comparatively small amount of ^{7}Be (less that 50%) in sediments toward the end of the period of summer stratification. The distribution is uniform and unrelated to sediment accumulation patterns. Robbins and Eadie (1991) showed that, at a 100 m deep site in southern Lake Michigan, very little ^{7}Be reached underlying sediments once the lake had stratified because of a combination of epilimnetic recycling and lower mean settling rates of particulate material. The radionuclide is probably inefficiently transferred to sediments at the HiDep site as well. By the next collection period, Feb-Mar, 1999, the lake had de-stratified and, with overturn, the inventory of ^{7}Be (Fig. 9, upper right) had been shared between water and sediments. Still, the pattern does not resemble the long-term pattern of mass accumulation. However there are sites within the HiDep area which have received more ^{7}Be than is present in the lake on average. The next collection period, April-May, 1999, occured after the primary winter EREs and an excursion of a turbidity "plume" over the HiDep area. A band of significantly elevated ^{7}Be inventories (Fig 9, lower left) traverses a northward running pathway across the HiDep area, but the pattern still does not resemble NMAR contours. Rather, it resembles the March 12, 1999 satellite image of surface reflectance (Fig. 10), i.e. the "turbidity plume" associated with the primary wind-driven re-suspension event of 1999. The figure illustrates the characteristic offshore divergence over the HiDep area. The association is sufficiently compelling to conclude that the turbidity plume is instrumental in conveying additional ^{7}Be to the coring site, either by scavenging additional amounts of the radionuclide from water or through re-suspension of ^{7}Be labeled sediments from outside the HiDep area. A corollary then is that, while individual re-suspension episodes may allocate new mass to the Hi Dep area, the initial pattern of deposition is plume-specific. Thus the long-term NMAR distribution might be the average result of many annual ERE plumes traversing the HiDep area. Alternatively, new mass allocations might be horizontally re-organized to form the NMAR patterns on shorter than annual time scales by unrecognized processes. The latter option is favored by final observations of the ^{7}Be inventory distribution.

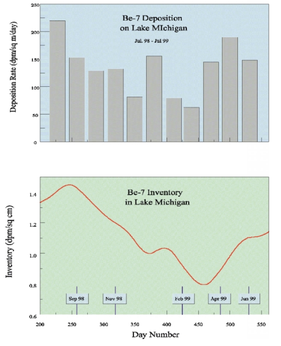

Fig. 8. (a) Atmospheric flux of ^{7}Be to Lake Michigan based on monthly atmospheric concentration measurements from September 1998 through July 1999 at Argonne National Laboratory, Argonne, IL. (b) Resulting seasonal variation of the ^{7}Be inventory in lake sediments and water column.

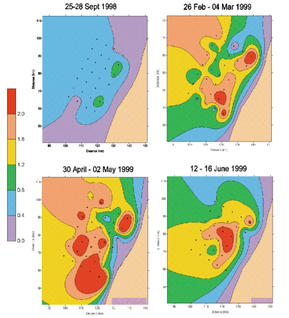

Fig. 9 Inventory of ^{7}Be in sediments at the HiDep site, normalized to lake inventory, for the four core principal collection periods: Sept 1998, Feb 1999, April 1999 and June 1999 All contour plots have identical scaling and color value assignments (upper left panel).

Post-ERE redistribution of particles?

On the last collection period in June 1999, when the lake had been stratified for approximately a month and new additions of ^{7}Be to sediments were attenuated, the inventory (Fig. 9, lower right), which is largely the remnant of accumulations during March and April, finally resembled the NMAR distribution. Between the end of March and Mid-June, the thermal bar developed and progressed outward from the shore completing the lake stratification process during May. In that time diatom blooms developed and passed and, following the establishment of the epilimnion, other planktonic production commenced. As result sediment cores collected in June had a new layer of highly flocculent, pigmented material associated with a detrital rain. Perhaps some combination of physical and biological processes operating during the critical months of April and May can promote a horizontal redistribution of previously imported particles to their final resting places in the HiDep area.

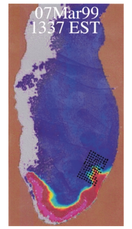

Fig. 10. HiDep coring sites with superimposed satellite image of surface reflectance during the principal winter episodic re-suspension event in March 1999.

Conclusions

Radionuclides employed in this study are useful indicators of short- and long-term particle transport processes.

Inventories of ^{137}Cs can be used to infer net mass accumulation rates (NMARs) of sediment in the HiDep area.

The resultant high-resolution contour map reveals a strongly focused NMAR region that tilts offshore within the HiDep area.

The tilt is consistent with the water circulation patterns set up during later winter storms and with satellite images of surface reflectance (turbidity) that diverge offshore in the HiDep area.

Excursion of the March 1999 turbidity "plume" over the HiDep area elevated sedimentary inventories of 7Be approximately along its path.

The ^{7}Be inventory resembled the long-term pattern only well after the lake had stratified.

Horizontal, kilometer scale transport of mass within meters of the sediment-water interface may be important throughout the year for horizontal redistribution and net accumulation of sediments in the HiDep area.

Acknowledgement

The lake-wide inventories of ^{137}Cs and mass accumulation rates were obtained between 1992 and 1996 by the Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration and the WATER Institute of the University of Wisconsin-Milwaukee as part of the EPA-supported Lake Michigan Mass Balance (LMMB) study.

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